TOPEX/POSEIDON Mission Overview

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Abstract

TOPEX/POSEIDON, a space mission jointly conducted by the United States and France, is the first space mission specifically designed and conducted for the study of the circulation of the world oceans. A state-of-the-art molar altimetry system is used to measure the precise height of sca level, from which infori nation on the global geostrophic currents of the upper ocean is obtained. The satellite, launched on August 10, 1992, has been making observations of the global oceans with unprecedented accuracy since late September, 1992. To meet the stringent measurement accuracy required for ocean circulation studies, a number of innovative improvements have been made to the program, including the first dual- frequency spac~-borne radar altimeter capable of retrieving the ionospheric delay of the radar signal, a three-fmqucncy microwave radiometer for retrieving the signal delay caused by the water vapor in the troposphere, an optimal model of the earth's gravity field and multiple satellite tracking systems for precision orbit determination. Additionally, the satellite also carries two experimental instruments to demonstrate ncw technologies: a single-frequency solid-state altimeter for the technology of low power/weight altimeter and a Global Positioning System receiver for continuous, precise satellite tracking. The performance of the mission's measurement system has been validated by numerous verification studies. "l'he results indicate that the root-sum-square accuracy of a single-pass sca level measurement is 4.7 cm, more than a factor of two better than the requirement of 13.7 cm. This global data set is being analyzed by an international team of 200 scientists for the understanding of global ocean dynamics as well as marine geophysics and geodesy. The mission is designed to last for at least 3 years with a possible extension to six years. This multi-year global data set will go a long way toward the improvement of the understanding of the ocean's role in global climate change. A summary of the mission's systems and their performance as well as the mission's science plans is given in the paper.

1. introduction

On August 10, 1992, the TOPEX/POSEIDON satellite was launched by an Ariane 42P rocket from the European Space Agency's Guiana Space Center in French Guiana. This space mission has been conducted jointly by the United States National Aeronautics and Space Administrate ion (NASA) and the French space agency, Centre National d'Etudes Spatiales (CNES), and is using a state-of-the-art radar altimetry system to measure the precise height of the sea surface for studying the dynamics of the circulation of the world's oceans. The ultimate science goal of the mission is to make contributions to the understanding of the role of ocean circulation in global climate change. Other applications of the mission's measurements include ocean tides, marine geodesy and geophysics, ocean wave height and wind speed.

The scientific utility of satellite altimetry has been demonstrated by the Seasat Mission (Journal of Geophysical Research, Vol.87, No. C5, 1982, and Vol. 88, No. C3, 1983) and the Geosat Mission (Journal of Geophysical Research, Vol. 95, Nos. C3 and C1 O, 1990). Also orbiting in space today is another radar altimeter aboard the European Space Agency's ERS-1 satellite. Many interesting and useful results about ocean currents have been obtained from these missions. However, these results are not sufficiently accurate for addressing many of the the aspects of large-scale ocean circulation because none of the missions were specifically designed and conducted for the study of ocean circulation as was "1'01'13XWOS];IIX3N. To be useful for studying ocean circulation, especially at the gyre and basin scales, numerous improvements have been made in TOPEX/POSEIDON, including specially designed spacecraft, sensor suite, satellite tracking systems, and orbit configuration, as well as the development of an optimal gravit y model for precision orbit determination and a dedicated ground system for mission operations. Another unique aspect of the mission was the formation of a Science Working

Team (SWT) early in the mission planning phase (5 years before launch) to ensure a close dialog between the science users and the mission development team.

Within 43 days from launch the mission's operat ion team completed satellite and sensor check-out and the adjustment of the injection orbit into the operational orbit. Collection of science data began on Septem ber 23, 1992. Since then the satellite has been orbiting the earth at an altitude of 1336 km with an inclination of 66 degrees, making sea surface height measurements along the same surface tracks, within +/- 1 km, every 10 days. The mission was designed to operate for a minimum of 3 years, with sufficient expendables carried to allow a 2-year extended mission if the satellite and sensors arc still functioning properly at the end of the primary mission. Plans are also being developed for a 3 year extended mission.

During the first six months of the mission, the primary objective was to calibrate the mission's measurement system and verify its performance. The TOPEX/POSEIDON Project established two dedicated sites for this calibration/verification effort: Point Conception off the coast of California, and the 1 .ampedusa Island in the Mediterranean Sea. Verification campaigns have also been conducted by mission scientists at a number of sites around the world. During this Verificat ion Phase, the mission's Precision Orbit Determination (POD) Team used the various satellite tracking data to fine tune the gravity field model and other force models, as well as tracking station coordinates for computing the precise orbit for the mission.

The Verification Phase was completed at the end of February, 1993. A workshop involving the mission engineers and scientists was held then to review the verification results. The conclusions of the workshop indicated that all the measurement accuracy requirements had been met and many of the measurement performances had exceeded requirements. After minor modification of the science algorithms based on the workshop results, the mission's ground system began processing and distribution of the Geophysical Data Record (GDR), the baseline science data product of the mission, in late May, 1993.

"l'his paper provides a summary of the mission's major elements and the results of the Verification Phase including an overall assessment of the mission's measurement performance. It is intended to serve as a framework for the other more detailed articles collected in this special issue.

2. The Satellite

The TOPEX/POSEIDON satellite is an adaptation by Fairchild Space of the existing Multi-Mission Modular Spacecraft (MMS), which has successfully carried the payloads of the Solar Maximum Mission, Landsat-4 and Landsat-5. The MMS design was modified to meet the TOPEX/POSEIDON requirements. The satellite consists of the MMS bus and the instrument Module which houses the instrument complement, Shown in Figure 1 is the fully deployed TOPEX/POSEIDON satellite featuring the major modules, sensors, and antennas.

Within the MMS, the Command and Data Handling Subsystem includes the onboard computer and tape recorder and provides control for all satellite engineering subsystems and sensors. The Attitude Determination and Control Subsystem and the Propulsion Subsystem control attitude throughout the mission, in cruise, and during maintenance and orbit-adjust maneuvers. The Electrical Power Subsystem on the MMS provides power from the solar array and batteries to the satellite systems for the duration of the mission. The solar array is mounted to the instrument Module, and its motion is controlled by the Solar Array Drive Assembly. The Radio Frequency Communications

Subsystem includes the high-gain antenna and the omni-directional antennas and provides forward- and return-link telecommunications capability. The satellite uses the Tracking and Data Relay System (TDRS) for communications with the Project Operation Control Center at J]’]..

3. Science Instruments

There arc six science instruments in the mission’s payload, four from NASA and two from CNES. They are divided into operational and experimental sensors as follows:

(1) Operational Sensors

(a) Dual-Frequency Radar Altimeter (ALT) (NASA).
(b) TOPEX Microwave Radiometer (TMR) (NASA).
(c) Laser Retroreflector Array (LRA) (NASA).
(d) Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) Dual Doppler Tracking System Receiver (CNES).

(2) Experimental Sensors

(a) Single-Prcqucncy Solid-State Radar Altimeter (SSALT) (CNES).
(b) Global Positioning System Demonstration Receiver (GPSDR) (NASA).

The Al .’J’, which is the first spaceborne dual-frequency altimeter, is the primary instrument for the mission (Ziegcr et al., 1991; 1 lancock et al., 1994). The measurements made at two frequencies (5.3 and 13.6 GHz) are combined to minimize the errors caused by the ionospheric free electrons, of which the total content is obtained as a by-product of the measurement. The ALT was developed and built by the Applied Physics Laboratory of the Johns Hopkins University (APL/JHU) under contract to the Wallops Flight Facility of NASA's Goddard Space Flight Center (GSFC) on behalf of JPL. The ALT design is based on the previous Seasat and Geosat altimeters with significant improvements including the 5.3 GHz channel for the ionospheric measurement, a more precise height measurement, and longer lifetime.

The TOPEX Microwave Radiometer (TMR) makes use of the measurement of sea-surface microwave emissivity at three frequencies to estimate the total water-vapor content in the atmosphere; this estimate is used to correct for the water-vapor-induced errors in the altimeter measurement. The 21-GHz channel is the primary channel for water-vapor measurement. The 18-GHz and 37-GHz channels are used to remove the effects of wind speed and cloud cover, respectively, in the water-vapor measurement. The TMR was developed and built by the Observational Systems Division of the Jet propulsion Laboratory (JPL), California Institute of Technology (Ruf et al., 1994).

The Laser Retroreflector Array (LRA), built by APL/JHU, is used with a network of Satellite Laser Ranging (SLR) stations, managed by GSFC, to provide satellite tracking data for precision orbit determination (POD) and calibration of the radar altimeter bias.

The DORIS tracking system of CNES provides another type of satellite tracking data using microwave Doppler techniques (Nouel et al., 1989). The system is composed of an onboard receiver and a network of ground transmitting stations. These stations, equipped with meteorological sensors measuring temperature, humidity and atmospheric pressure for correcting for atmospheric effects on the transmitted signals, provide a quasi-continuous tracking of the satellite (80% of the time).

Both SLR and DORIS data are used in the POD process, including gravity model tuning. The DORIS signals are transmitted at two frequencies (401.25 and 2036.25 MHz) to allow the removal of the effects of the ionospheric free electrons in the tracking data (Picot and Escudier, 1994, unpublished manuscript), Therefore, the total content of the ionospheric free electrons can also be estimated from the DORIS data and used for the ionospheric correction for the SSALT. However, the electron content estimate from DORIS is based on slant range observation and must be interpolated to the altimeter nadir path, resulting in larger uncertainty in the path delay retrieval than the dual-frequency ALT estimate.

The two experimental instruments are intended to demonstrate new technologies. The successful operation of the SSALT, a solid-state Ku-band (13.65 GHz) altimeter, has validated the technology of a low-power, low-weight altimeter for future earth-observing missions (Zanife et al., 1994, unpublished manuscript). It shares the same antenna with the ALT. Therefore the two altimeters cannot operate at the same time. During the initial 6-month verification phase of the mission, the CNES altimeter operated for 12.5% of the time to assess its performance. This 12.5% of operation time was optimized for the overflight of the SSALT over the two verification sites. Since the completion of the verification phase, the SSALT has been operating for one complete 10 day cycle approximately every 10 cycles (see Section 5.1). The SSALT was designed by CNES and built by Alcatel Espace.

The GPSDR receives signals from the GPS constellation. With a combination of the GPSDR data and a number of GPS receivers on the Earth's surface, precise, continuous tracking of the spacecraft is made possible by using the technique of Kalman filtering and differential ranging. The continuous tracking has made POD possible with lesser need of accurate gravity and spacecraft modeling. The successful operation of the GPSDR and the excellent quality of the orbit ephemerides produced from the experiment has demonstrated the technology for POD in the future (Bertiger et al, 1994). The GPSDR was developed and built by Motorola under contract to J]>]..

4. Orbit Configuration

Many factors influence the determination of the mission's orbit configuration (Parke et al., 1987). The inclination and repeat period of the orbit determine how the ocean is sampled by the satellite. A major concern is aliasing the tidal signals into frequencies of ocean-current variabilities. inclinations that lead to undesirable aliased tidal frequencies -- such as zero, annual, and semi-annual-- are to be avoided. In order to determine the ocean tidal signals from the altimetry measurement and subsequently remove them for the study of ocean circulation, inclinations that make different tidal constituents aliased to the same frequency should also be avoided. To satisfy these constraints and yet cover most of the world oceans, an inclination of 66 degrees was selected.

For a single satellite mission, temporal resolution and spatial resolution are in competition: the higher the temporal resolution, the lower the spatial resolution, and vice versa, A repeat period of 10 days (9.916 days to be exact) is the best compromise; it results in a equatorial cross-track separation of315 km.

To maximize the accuracy of orbit determination, a high orbit altitude is preferred because of reduced atmospheric drag and gravity forces acting on the satellite. A major disadvantage of a high orbit is the increased power needed by the altimeter to achieve the required level of signal-to-noise ratio. A compromised orbit altitude is in the range of 1200 to 1400 km. The exact altitude that allows the orbit to satisfy all other constraints and fly over the two verification sites is 1336 km. Shown in "1'able 1 are the characteristics of the mission's operational orbit.

S. Mission **Operations**

Mission operations (e.g., satellite control and data processing) are conducted by JPL at Pasadena, California. CNES has implemented an information Processing Center (IPC) at Toulouse, France for CNES sensor control and data processing via an interface with the Ground System at JP1.. A top priority for mission operations is to maximize the collection of high-quality data and to process and distribute them in a timely manner. Through a series of six orbit maneuvers, the mission's navigation team adjusted the altitude, inclination, and eccentricit y of the satellite's orbit to the specifications of the mission's operational orbit. After this milestone, the satellite's ground track has been maintained within 1 km from the nominal tracks since mid October, 1993 (Figure **2).** Periodic orbit maintenance maneuvers have been performed to strictly observe this requirement. In order to minimize the impact to science investigation, special efforts arc made to maximize the period between the orbit maneuvers and to conduct the maneuvers over land.

After the operational orbit was achieved, the collection of the mission's science data began. The data have been grouped into 10-day orbit cycles with each cycle starting at the equatorial crossing of 99.92 degrees East.

5.1 Verification

Verification of the performance of the satellite and the instruments and the integrity of the science data is a continuing process involving participation from both the mission engineers and scientists. However, during the first 6 months of the mission, an intensive verification campaign was conducted jointly by NASA and CNES to calibrate and verify satellite measurements of geophysical parameters against in situ data at two verification sites. In addition, the satellite laser ranging and DORIS data were used to validate precision orbit determination and to tune the gravity-field model that was to be used for the POD in the GDR production,

NASA instrumented an oil platform (owned by Texaco) 12 km west of Point Conception, California, to obtain data on sea level and related parameters (Christensen et al, 1994 a). Sea level measurements were made by an acoustical device and pressure gauges mounted on the oil platform. The sea-level data along with the various precision orbit ephemerides based on laser, DORIS, and GPSDR data were used to determine the distance between the satellite and the sea surface; this distance was then compared with the altimeter-height measurement to determine the altimeter bias and bias drift. Other instrumentation at the oil platform included a GPS receiver for determining the absolute height of the platform and the total electron content, a surface pressure gauge for dry-troposphere correction, and an upward-looking water-vapor radiometer for the wet-troposphere correct ion.

The primary CNES verification site was near Lampedusa Island in the Mediterranean Sea (Menard et al. 1994). CNES instrumented a small islet, Lampione, located 18 km west of Lampedusa island. The instrumentation configuration included a laser on Lampedusa, two tide gauges on Lampione, two tide gauges on the west side of

Lampedusa, a DORIS station on Lampedusa, two ground-based radiometers, a meteorological station, two GPS receivers (for ionospheric measurement), and two GPS buoys south of Lampione..

in addition to these two dedicated verification experiments, numerous studies have been conducted by the mission's science teams to assess the performance of the mission's measurement system. The results from those studies form the core of this special issue. A summary of the assessment is given in Section 6.

S.2 **Altimeter Antenna Sharing**

An important task for the mission operation is to operate the two radar altimeters (ALT and SSALT) according to the mission plan. During the Verification Phase, the priority was to share the verification site overflights equally between the two altimeters, The SSALT was operating for 12.5% of the time, including 60% of the overflights of the Lampedusa verification site and 40% of the Harvest site. This 12.5% also included a 3-day subcycle every 5 cycles. Upon the completion of the Verification Phase, it was felt that complete cycles of 10-day SSALT data were mom desirable for science applications as well as certain performance evaluations (e.g., the sea-state bias). Therefore, the SSALT has been operated for one complete 10-day cycle approximately every 10 cycles since April, 1993, with the exact schedule determined so as to minimize the residual ionospheric errors (after correction using the DORIS data). Coordination with certain field campaigns to validate SSALT was another factor in formulating the current plan.

5.3 Data Processing and Distribution

The primary data product for scientific research is the Geophysical Data Record (GDR), which includes the altimeter sea-level height measurements, associated corrections, ancillary data, and measurement locations based on the precision orbit ephemeris. The GDR, based on algorithms validated by the science teams, has been generated on a global basis since late May, 1993. The format of the GDR is similar to that of Seasat and Geosat; however, the content of the data is larger (Callahan, 1994; AVISO, 1992). The data return rate has been about 98 % without systematic data losses over any geographic regions.

NASA and CNES are processing GDRs for each agency's own altimeter measurement. The data flow is illustrated in Figure 3. The NASA GDR (designated as GDR-T), which does not contain the SSALT data, are available on magnetic tapes after about one month after data reception via the JPL Physical Ocean Distributed Active Archive Center (PO-DAAC). The CNES GDR (GDR-P), containing only the SSALT data, is combined with the NASA GDR to form the merged GDR (M-GDR), which is available on CD-ROMS about 45 days after the data reception via the French data agency, AVISO. The JPL PO-DAAC is also producing identical merged GDR CD-ROMs on similar schedule. in addition to the GDRs, the NASA and CNES IGDRs are available within 5-7 days of data reception via electronic transmission through the computers of PO-DAAC and AVISO to operational users for environmental monitoring purposes.

S.4 Anomalies

There were two anomalies in the satellite system during the early phase of the mission. First, the pointing error of the altimeter boresight was anomalously high during the first 2 months of the Verification Phase. The problem was corrected in December, 1993, after a series of altimeter boresight calibrations, attitude system calibrations, and flight software corrections. Figure 4 shows the history of the altimeter pointing during Cycles 4-14. The off-nadir angle has settled to about 0,05 degrees after Day 355 (Dec. 20, 1992), The one-sigma requirement for the pointing is 0.08 degrees. Therefore, since Dec. 20, 1992, the altimeter pointing has been better than the requirement.

The second anomaly was the failure of one of the two star trackers of the satellite's attitude control system on November 25, 1993. This failure was apparently caused by a single event upset and the damage might not be permanent. Recycling its power may bring it back. However, the combination of the remaining star tracker and the digital fine sun sensor has been able to meet or exceed the attitude performance requirement. Therefore, no attempts have been made to revive the failed star tracker.

6. Assessment of the Measurement System

The mission's primary measurement is the height of the sea surface relative to a reference ellipsoid. This sca surface height is derived by subtracting the altimeter measurement of the altitude of the satellite above the sea surface from the altitude of the satellite above the reference ellipsoid obtained from the POD. The accuracy of the sea surface height is thus determined by the accuracies of the altimeter and the POD.

6.1 Altimeter Performance

There are various sources of error in the altimeter height measurement. They arc discussed as follows.

Measurement Noise

A spectral analysis was performed to estimate the noise of both the ALT and the SSALT range estimations (Menard, 1993). A large number of data segments of 10 second duration (62 km in length) at 101174 data rate (10 data points per second) were analyzed. The noise level was determined by the white noise level at the high-frequency end of each spectrum. Displayed in Figure 5 are the plots of the instrument noise at 1 Hz data rate as a function of the significant wave height (SWH) for both the ALT and the SSALT. The ALT noise varies from 1.7 cm at 2 m SWH to a relatively stable value of 2 cm for SWH larger than 3 m. The SSALT had a higher noise level, especially before Cycle 41. Based on simulations and wavveform retracing, the SSALT on-board algorithm coefficients have been adjusted since Cycle 41. This adjustment has improved the SSALT noise figure by 20%, varying from 2 cm at 2 m SWH to 2.8 cm at 5 m SWH.

Mispointing and Skewness Effects

Due to the simplified calculation performed to the altimeter wave form onboard the satellite, altimeter range, SWH, and AGC (automatic gain control, a quantity used for calculating sigma-0) need to bc corrected on the ground for the effects of sea state and altimeter pointing angle (Chelton et al., 1989). The correction was implemented in the form of polynomials for the ALT (Hayne et al, 1994) and table look-up for the SSALT (Zanife et al., 1994, unpublished manuscript). The coefficients of the polynomials and table look-ups were estimated by analyzing simulated altimeter wave forms before launch and revised by analyzing the real wave form data collected after launch. Rodriguez and Martin (1994 a) made extensive comparisons of the GDR data with results from retracking the wave form data. They reported that the residual errors after the correction were largely caused by the effects of the skewness of ocean surface specular point probability density function that had not been accounted for by the GDR corrections. Such comparisons serve as verification of the effectiveness of the GDR correction algorithm. The estimated rms skewness-induced error is 1.2 cm for the Ku-band and 2.2 cm for the C-band (Rodriguez and Martin, 1994 a). The error occurs primarily at scales larger than about 600 km. Similar analysis was performed to one cycle's worth of wave form data from the SSALT. The result suggests that the skewness-induced error in the SSALT data were also about 1.2 cm (E. Rodriguez and O. Zanife, personal communication).

EM Bias

It is well known that the radar backscatter cross section is larger at wave troughs than at wave crests (e.g. Walsh et al., 1989). Therefore, altimeter-measured sea surface height is biased toward wave troughs and this bias is called the electromagnetic bias, or EM bias. EM bias is roughly proportional to the height of waves and is normally expressed in terms of a percentage of SWH. The percentage has been found to be sensitive to wind speed and a quadratic dependence on wind speed was used in the NASA GDR algorithm (Callahan, 1993; Hevizi et al., 1993). Because the EM bias is dependent on radar frequency, the coefficients of the algorithm are slightly different between the Ku- and C-band.

Analyses of the correlation between altimeter height and SWH have suggested that them is a residual EM bias error of about 1 % of SWH in the GDR (Rodriguez and Martin, 1994 b). For a typical SWH=2m, the residual EM bias error is about 2 cm. The present CNES EM bias algorithm is based on the method of Fu and Glazman (1991) that parameterizes the EM bias in terms of a quantity called the pseudo wave age. The performance of this algorithm is somewhat inferior to the NASA algorithm and shall be replaced in the future by the new EM bias parameterization of Gaspar et al. (1 994).

Ionospheric Error

The range delay caused by the ionospheric free electrons is retrieved by the dual frequency measurements of the ALT when it is in operation. When the SSALT is in operation, this correction is derived from the dual frequency signals received by the DORIS receiver. The ALT retrieval is the most direct method of estimating the first-order ionospheric error, whereas the DORIS approach requires space-time interpolation to the altimeter nadir path. However, there are two error sources in the ALT retrieval: the noise in the altimeter measurements and the residual frequency-dependent EM bias and skewness bias. The former has been estimated to be about 0.5 cm at 1 Hz data rate and can be reduced to about 0.1 cm by averaging over 100 km along track because **there** is little signal variance at wavelengths shorter than 100 km (Imel, 1994). The latter has to do with the frequency dependence of the EM bias and the skewness bias. The difference between the residual Ku- and C-band EM bias was found to be less than 0.5% of the SWH (Imel, 1994), resulting in an error in the range delay retrieval of 0.2 cm for a typical SWH of 2 m. As noted above, the skewness bias is also frequency-dependent, i.e., 1.2 cm for the Ku band and 2.2 cm for the C-band (rms estimates based on wave-form retracing). Because the Ku- and C-band errors are uncorrelated, they introduce another 0.45 cm error into the ionosphere correction. Thus the total ionosphere correction error is about 0.5 cm.

The rms error of the DORIS-derived correction is estimated to be 1.7 cm by comparison with the ALT dual-frequency measurement (Picot and Escudier, 1994, unpublished manuscript). However, the error has a geographic pattern with the largest values located in the tropics and subtropics.

Wet Tropospheric Error

The water vapor in the troposphere causes delay in the propagation of radar signal. This "wet tropospheric error" is related to the total columnar water vapor content in the altimeter nadir path. The brightness temperatures measured in the three frequency channels of the TMR were used to retrieve the wet tropospheric correction. By comparing the TMR observations with ground based water vapor radiometer and radiosonde observations, the nns accuracy of the wet tropospheric correction is estimated to be about 1.2 cm (Ruf et al., 1994). Another correction available on the GDR is provided by the French Meteorological Office (FMO) based on products issued by the European Center for Medium-Range Weather Forecast (ECMWF). Therms difference between this correction and the TMR-based correction is about 3 cm (Stum,1 994). Morris and Gill (1994) found an average improvement of 2.3 cm over the Great Lakes when the TMR correction was used instead of the FMO/ECMWF correction.

Dry Tropospheric Error

The radar signals are also delayed by the dry air mass of the troposphere, at a rate of 0.27 cm pcr mb of atmospheric sea level pressure. The correction for this dry tropospheric error is made by using the sca level pressure product of the ECMWF provided by the French Meteorological Office. The nns accuracy of the correction is estimated to be 0.7 cm based on an assumption of an rms 3 mb accuracy of the atmospheric pressure product.

Altimeter Bias and Drift

Determination of the bias in the altimeter height measurement and its possible drift in time was a major objective of the verification experiments conducted at the two verification sites. Based on the first 36 cycles of data, a bias estimate of -14.5 +-/- 2.9 cm was obtained for the ALT height measurement (Christensen et al. 1994a). The negative value indicates that the altimeter range is measured short. No unambiguous drift in the bias estimates has been determined.

The bias in the SSALT measurement was estimated to be 1.0 +/- 2.4 cm (Menard et al., 1994). The relative bias between the ALT and SSALT was investigated by a number of groups based on direct analysis of the altimeter data (e.g., Le Traon et al., 1994; Minster et al., 1994; Shum et al., 1994; Morris and Gill, 1994). The results are consistent with the findinds at the two verifications sites to the extent of the error estimates.

However, Note that all the bias estimates are dependent on the particular EM bias algorithms used. With various EM bias corrections applied, the ALT bias ranged from -13.1 cm to -17,1 cm, whereas the the SSALT bias ranged from -0.2 cm to 9.5 cm (Christensen et al., 1994). The definitive ALT and SSALT bias estimates quoted in the preceding two paragraphs were based on the NASA GDR algorithm (Callahan, 1994; Hevizi, 1993) and the new algorithm of Gaspar et al. (1994), respectively.

<u>Altimeter SWH and Radar Backscatter Coefficient</u>

Callahan et al. (1994) compared the SWH and radar backscatter coefficient (called sigma-0 in practice) measured by ALT to both Geosat and buoy observations. They found that the ALT sigma-0 was biased higher than the Geosat sigma-0 by 0.7 dB. After removing this bias, the wind speeds derived from the ALT sigma-0 using a Geosat algorithm agreed with buoy observations within 2 m/s. Monthly histograms of both SWH and sigma-O agree fairly well with the Geosat results. The SWH agrees with the buoy observations within 0.2 m.

6.2 Precision Orbit Determination Performance

The uncertainty in the radial component of the satellite orbit has long been the largest error source in satellite altimetry. A long-lead effort to improve the knowledge in the earth's gravity field was funded by the TOPEX/POSEIDON Project as a key step toward a significant improvement in the POD capability to meet the mission's science goals (Marsh et al., 1988, 1990; Tapley et al., 1988; Lerch et al., 1993). The post-launch gravity improvement activities were conducted as a joint effort by GSFC, the University of Texas at Austin, and CNES (Nerem et al., 1994). In addition to the gravity improvement effort, the satellite's sophisticated tracking system - the satellite laser ranging plus the DORIS system as the baseline system with the GPSDR as an experimental system - has made the TOPEX/POSEIDON POD a revolutionary achievement (Tapley et al., 1994; Nouel et al., 1994). Other factors for the achievement include a joint American and French effort in the development and improvement of force modeling, reference systems, station coordinates and numerical methods. The resulting rms accuracy of the baseline precision orbits (used for producing the GDR) computed by using the laser and DORIS data is estimated to be 3.5 cm. Most of the error is random and can be reduced by time-averaging. The systematic component, which is correlated geographically and cannot be reduced by time-averaging, is estimated to be less than 2 cm. Both the U.S. and France are producing independent precision orbit products with comparable accuracies. The U.S. effort is led by the GSFC with support from the Center for Space Research of the University of Texas at Austin and the Colorado Center for Astrodynamics Research of the University of Colorado at Boulder. The French effort is conducted by the Service d'Orbitographie Doris (SOD) at CNES.

Precision orbit is also computed at J}]]. using the GPS tracking data (Bertiger et al., 1994). Because of the quasi-continuous tracking of the satellite via the GPS constellation, the orbit solution is less dependent on the gravity model and has been demonstrated to be useful for studying the geographically correlated error in the Laser/DORIS orbit. The accuracy of the so-called reduced dynamic orbit solution is estimated to be 3 cm. Christensen etal(1994b) were able to relate the differences between the GPS-based orbit and the laser/DORI S-based orbit to the geographical y correlated errors in the latter due to gravity model errors. However, when the anti-spoofing (an operation conducted by the U.S. Air Force periodically for military purposes) is operating, the orbit accuracy is slightly degraded (with errors about 4-5 cm, W. Bertiger, persona] communication).

6.3 An Error Budget

Shown in Table 2 is an estimate of the error budget for the TOPEX/POSEIDON altimeter height measurement based on the discussions given above. Separate estimates are given for the TOPEX system (the Al .T with the NASA algorithms and orbit) and the POSEIDON (the SSALT/DORIS with the CNES algorithms and orbit). The error is given in terms of root-sum-square for 1/see data rate and 2 m SWH. Note that the skewness bias for the SSALT measurement has not been determined yet. The total measurement error is significantly less than the mission requirement, which specifics a total error of 13.7 cm, of which 12.8 cm was allocated to POD. The superb POD performance is thus the key to the better-than-specification sea level accuracy. For the first time the users of altimetry data are no longer required to reduce orbit errors using empirical techniques that often have reduced ocean signals as well. "l'his improvement is especially critical to the study of large-scale, weak signals, a major objective of the mission.

There arc a number of verification studies that have validated the error budget estimate. For example, Morris and Gill (1994) compared the ALT measurements to simultaneous tide gauge measurements taken around the Great Lakes, where natural variabilities arc very small, making the comparison an excellent approach to verification. They found an overall rms difference of 3 cm between the two measurements. However, the comparison only applies to the temporally varying component of the measurement. Therefore, the 3 cm difference is actually smaller than the estimated total error of 4.7 cm, which contains the time-invariant systematic component as well. Nercm et al. (1994) compared the T/P sea level observations to those made by a large number of tidea gauges in the tropical Pacific and obtained agreement within 2-4 cm.

7. Tidal Errors

As the accuracy of the altimetric measurement of sea level has reached a level that allows the detection of the large-scale weak signals of ocean currents, one has to be concerned with the tidal signals in the data. The tides are composed of the ocean tides and the body tides (including both the solid earth tides and the ocean loading tides). All the tides have been corrected for by model predictions (Callahan, 1993). The accuracy for the body tide models is probably better than 1 cm, whereas the accuracy of the ocean tides is of main concern.

Two ocean tide models arc supplied in the GDR: the Schwiderski Model (Schwiderski, 1980 a,b) and the Cartwright and Ray Model (Cartwright and Ray, 1990). The global rms difference bctwccn these two models is about 6 cm, with peak differences being as large as 15-20 cm (Cartwright and Ray, 1990). This difference is a rough measure of the accuracies of these models. More detailed studies of the two models have indicated that the global rms errors arc on the order of 4-5 cm for both models with the Cartwright and Ray Model being slightl y better (Ray ,1993; Monlines et al; 1994, Wagner et al., 1994). For the study of the large-scale ocean variabilities, improved ocean tide models arc required and arc under development (e.g. Egbert et al., 1994). By applying simple empirical methods to the TOPEX/POSEIDON data, several investigators have demonstrated that the errors of the ocean tide models can be improved to a level of 2-3 cm (Schrama and Ray, 1994; Wagner et al, 1994). More sophisticated approaches will certainly obtain better results.

8. Science investigations

The science investigations using the unique capabilities of TOPEX/POSEIDON are being carried out by the members of the SW]', which consists of 38 Principal Investigator teams selected by NASA and CNES, through the process of Announcement of Opportunity. Most of the Principal Investigators have a team of co-investigators, amounting to a science team totalling more than 200 members. The selection was made based on the scientific merit of the proposed investigations and their relevance to the mission's science goals. The Principal investigators' responsibilities are to deliver the main scientific results from the mission, The investigators and the titles of their investigations are listed in I'able 3. "l'here are sixteen Principal Investigators from the United States, thirteen from France, two from Japan, two from Australia, and one from each of the following countries: United Kingdom, South Africa, West Germany, Norway, and the Netherlands. The reader is referred to TOPEX/POSEIDON Science Working Team (1991) for a detailed description of the mission's science plan.

The main subject of the mission- -ocean circulation--is addressed by 29 investigators. Nine of them arc focused on the variability of basin-scale circulation of the ocean with no emphasis on any particular region: De Mey, Fu, Koblinsky, Liu, Minster, Olbers, Tai, Tarits, and Wunsch. Seventeen investigations have a regional focus: Born (the Northeast and the South Pacific), Burrage (North Australian regional seas), Chelton (the Southern Ocean), Church (the East Australian Current, the western South Pacific, and the eastern Indian Ocean), Desaubies (the tropical Atlantic), Cheney (tropical oceans), Grundlingh (the Agulhas Current), Katz (the tropical Atlantic), Lukas (the tropical Pacific), Arnault (the tropical Atlantic), Mitchell (the Gulf Stream and the Kuroshio), Ollitrault (the South Atlantic), Pettersson (the Norwegian Sea), Picaut (the tropical Pacific), Strub (the eastern Pacific), Imawaki (the western Pacific), and Woodworth (the Southern Ocean). Three investigations arc focused on the determination of the mean circulation and the geoid: Rapp, Tapley, and Wakker.

The remaining nine investigations addressed a variety of subjects including geodesy and geophysics: Barlier, Boucher, Cazenave, Segawa, Souriau, and Wahr; ocean tides: Le Provost and Sanchez; altimetry calibration and validation: Menard. Many of the 38 investigations cover a wide range of subjects; the grouping described above is based on the primary emphasis of each investigation. Ocean winds and waves is not the main subject of any of the investigations; however, it is a secondary objective of Woodworth's investigation.

The science plans briefly described above were formulated many years ago with a primary focus on the analysis of the altimetry data pcr sc. There are many new opportunities emerging from more recent developments. An important task for the SWT and the science community at large is to merge the TOPEX/POSEIDON data with other types of data and create a more comprehensive data set for the description of the global ocean circulation. Coincident with TOPEX/POSEIDON have been a variety of oceanographic and meteorological observat ions conducted as part of the World Ocean Circulation Experiment and the Tropical Ocean and Global Atmospheric Program. The TOPEX/POSEI DON data are providing a frame work to integrate these in-situ observations into a global perspective.

It is well known that a single satellite does not provide enough sampling to cover the complete spectrum of oceanic variabilities. 1 lowever, TOPEX/POSEIDON is providing the first accurate observation of the large-scale (larger than the mesoscale) part of the spectrum, the part that is least known from the past data, On the other hand, the ERS-1 altimeter data can be combined with the TOPEX/POSEIDON data to provide a more complete coverage in both spectral and physical domains (the latter refers to the areas between 66 and 82 degree latitude not covered by TOPEX/POSEIDON). The TOPEX/POSEIDON data, being more accurate than the ERS-1 data, can be used to calibrate the ERS- 1 data at the large scale (Le Traon et al., 1994), making the combined data set even more valuable for integration with the in-situ data.

To address many of the aspects of the ocean's role in climate change such as the transport of heat and carbon dioxide, one ultimately has to synthesize the global data sets with an ocean general circulation model. This synthesis process can be viewed as one of estimation problem, or as "data assimilation". Them is an urgent need for the science community to establish an effective approach to this important task. The result will lead to a framework, consisting of a global model or a set of models consistent with al l the key observations, for providing an optimal description of the state of ocean circulation that will serve to initialize air-sea coupled climate models.

9. conclusions

The TOPEX/POSEIDON mission has completed its first one and half year's operation quite successfully. The satellite as well as the instrument suite are healthy and performing nominal] y. Key milestones during this period of operation includes the completion of the Verification Phase and the production and distribution of the mission's baseline data products. The results of the verification studies have indicated that the mission's performance has exceeded the requirements. The nns accuracy of a single-pass sea level measurement is 4.7 cm, more than a factor of two less than the requirement of 13.7 cm. The satellite ground tracks have remained within 1 km from the nominal tracks for more than 98% of the time. The data return rate has been 98%.

The data processing and distribution has been proceeding on schedule. The NASA data product, containing only the data during the ALT operation that accounts for 90% of the data, is distributed on magnetic tapes within about 45 days of data reception. The CNES data product, containing the complete data from both the ALT and the SSALT (accounts for 10% of the data) operations, is distributed on CD-ROMs within about 60 days of data reception. The JPL PO-DAAC is also producing CD-ROMS that is identical to the CNES products with a comparable delivery schedule.

The mission's ground system also produces, on a best effort basis, quick-look data products, which arc available within 7 days of data reception to the operational users through an electronic medium. This quick-look data is based on an orbit ephemeris that has an accuracy of 10 cm, more than an order of magnitude better than the requirement. This quick-look data set has been available on a 100% basis, as opposed to the 40% requirement. 'l'his mission is the first ocean research mission that delivers high-quality data on a near-real time basis.

The two experiments of the mission, the SSALT and the GPS-based POD, were successfully carried out. These achievements have demonstrated new technologies for future altimetry missions, which will be conducted in a more streamlined fashion for monitoring the global ocean circulation on a long-term basis.

The mission's data products are being analyzed by an international team of some 200 scientists for the study of global ocean dynamics as well as ocean tides, marine geophysics and geodesy. The results of the verification work and preliminary science results constitute the core of this special issue.

The mission' life time was designed for a minimum of three years with a possible extension to five. This multi-year global data set, when integrated with other types of data and synthesized by numerical ocean models, will go a long way toward the improvement of the understanding of the ocean's role in global climate change.

Acknowledgments

The authors are the Project Scientists and Project Managers of the TOPEX/POSEIDON Mission. They would like to express deep gratitude to all the engineers and scientists who have devoted exceptional efforts to making the mission a success. The research described in the paper was carried out partly at the Jet Propulsion Laboratory, California Institute of '1'ethnology, under contract with the National Aeronautics and Space Administration, and partly at the Centre Spatial de Toulouse, Centre d'Etudes National Spatiales. The work was supported by the joint U.S./France TOPEX/POSEIDON Project.

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Figure Caption

Figure 1. TOPEX/POSEIDON satellite in its fully deployed configuration. Positive x-axis points toward the flight direction.

Figure 2. Time history of the distance between the actual ground tracks and their nominal locations at the equator. The first 6 Orbit Maintenance Maneuvers (OMM) are indicated.

Figure 3. Flow chart of the data streams among the various data processing and archiving facilities of the TOPEX/POSEIDON Mission.

Figure 4. Time history of the daily averaged altimeter off-nadir pointing angle from Cycles 4-14.

Figure 5. Estimation of the altimeter noise of the SSALT (upper panel) and the ALT (lower panel) as a function of significant wave height.

q'able 1. Characteristics of the operational orbit

Parameter	value
Mean elements	
Semimajor axis, km	7714.4278
Eccentricity	0.000095
inclination, deg	66.039
Intertial longitude of ascending node, deg	116.5574
Argument of perigee, deg	**90.0**
Mean anomaly, deg	253.130
Auxiliary data	
Reference equatorial altitude, km	1336
Nodal period, s	6745.72
Cycle (127 revs) period, days	9.9156
Inertial nodal rate, deg/day	2.0791
Longitude of equator crossing of pass 1, deg	99.947
Acute angle of equator crossings, deg.	39.5
Ground-track velocity, km/s	5.8

Table 2. A Preliminary Assessment of Measurement Accuracies (one sigma values in cm)

	ALT	SSALT
Altimeter Range		
Altimeter noise(1)	1.7	2.0
EM bias	2.0	2.0
Skewness	1.2	1.2
ionosphere	0.5	1.7(2)
Dry Troposphere	0.7	0.7
Wet Troposphere	1.1	1.2
Total Altimeter Range(3)	3.2	3.8
Radial Orbit Height(4)	3.5	3.5
Single-Pass Sea Height	4.7	5.2

Notes-

(1) Altimeter noise is based on 1-sec average at 2 m significant wave height (SWH). The SSALT noise estimate is based on the data collected since Cycle 41 after the adjustment of the SSALT on-board algorithm.

(2) Based on DORIS data.

(3) Altimeter bias and bias drift not included

(4) Post verification workshop estimate based on the JGM-2 gravity model

Talble 3. TOPEX/POSEIDON Principal Investigators

Name	Institution	Investigation
S. Arnault	Universite Paris VI, France	*The Tropical* Atlantic Ocean
F. Barlier	Groupe de Recherches de Geodesie Spatiale, France	The Western Mediterranean Sea
G. Born	University of Colorado, USA	Weakly Defined Ocean Gyres
C. Boucher	Institut Geographique National, France	Terrestrial Reference Systems
D. Burrage	Australian Institute of Marine Sciences	The Yorth-Australian Tropical Seas
A. Cazenave	Groupe de Recherches & Geodesie Spatiale, France	Marine Geophysics
D. Chelton	Oregon State University, USA	The Antarctic Circumpolar Current
R. Cheney	NOAA/National Geodetic Survey, USA	Ocean Dynamics and Geophysics
J. Church	Commonwealth Scientific and Industrial Research Organization, Australia	Tbe South Pacific, the Southern, and the Indian Oceans
P. De Mey	Groupe de Recherches de Geodesie Spatiale, France	Data Assimilation by Ocean Models
Y. Desaubies	Institut Francais de Recherche pour l'Exploration de la Mer, France	The Western Equatorial Atlantic Ocean
I -! Fu	Jet Propulsion Laboratory, USA	Gyres of the World Oceans
M. Grundlingh	National Research Institute for Oceanography, South Africa	The Oceans around South Africa
S. Imawaki	Kyushu University, Japan	TheWestern North Pacific Ocean
E. Katz	Columbia University, USA	The Tropical Atlantic Ocean
C. Koblinsky	NASA/Goddard Space Flight Center, USA	Ocean Circulation and the Geoid
C. Le Provost	Institut de Mechanique de Grenoble, France	Global Ocean Tides
T. Liu	Jet Propulsion Laboratory	Hem Balance of Global Oceans
R. Lukas	University of Hawaii, USA	Tropical Ocean Dynamics
Y. Menard	Groupe de Recherches de Geodesie Spatiale, France	Geophysical Validation of Altimetry
J. Minster	Groupe de Recherches de Geodesie Spatiale, France “	Mesoscale and Basin-scale Ocean Variability
J. Mitchell	Naval Oceanographic and Atmospheric Research Laboratory, USA	The Mid-Latitude Western Boundary Currents
M. Ollitrault	Institut Francais de Recherche pour l'Exploration de la Mer, France	The South Atlantic Ocean

Table 3. (continued)

Name	Institution	Investigation
L. Pettersson	University of Bergen, Norway	The Nordic *Seas*
J. Picaut	Groupe SURTROPAC, ORSTOM, New Caledonia	The Tropical Pacific Ocean
R. Rapp	Ohio State University, USA	Mean Sea Surface arrd Gravity
B. Sanchez	NASA/Goddard Space Flight Center, USA	Global Ocean Tides
J. Schroeter	Alfred Wegener Institute for Polar and Marine Research, Germany	Ocean Circulation Modeling
J. Segawa	University of Tokyo, Japan	Marine Geodesy astd Geophysics
A. Souriau	Groupe de Recherches & Geodesie Spatiale, France	Plate Motions
T. Strub	Oregon State University, USA	Equatorial and Eastern Boundary Currents
C.-K. Tai	NOAA/National Geodetic Survey, USA	The Pacific Ocean
B. Tapley	University of Texas at Austin, USA	Ocean Surface Topography
P. Tarits	Institut de Physique du Glob& Paris, France	Altimetry Analysis with Sea Floor Electric Data
J. Wahr	University of Colorado, USA	Oceanic Effects on *the* Earth's Interior
K. Wakker	Delft University of Technology, the Netherlands	Orbit Computation and *Sea-surface* Modeling
P. Woodworth	Proudman Oceanographic Laboratory, United Kingdom	Marine Research
C. Wunsch	Massachusetts Institute of Technology, USA	Global Ocean Circulation

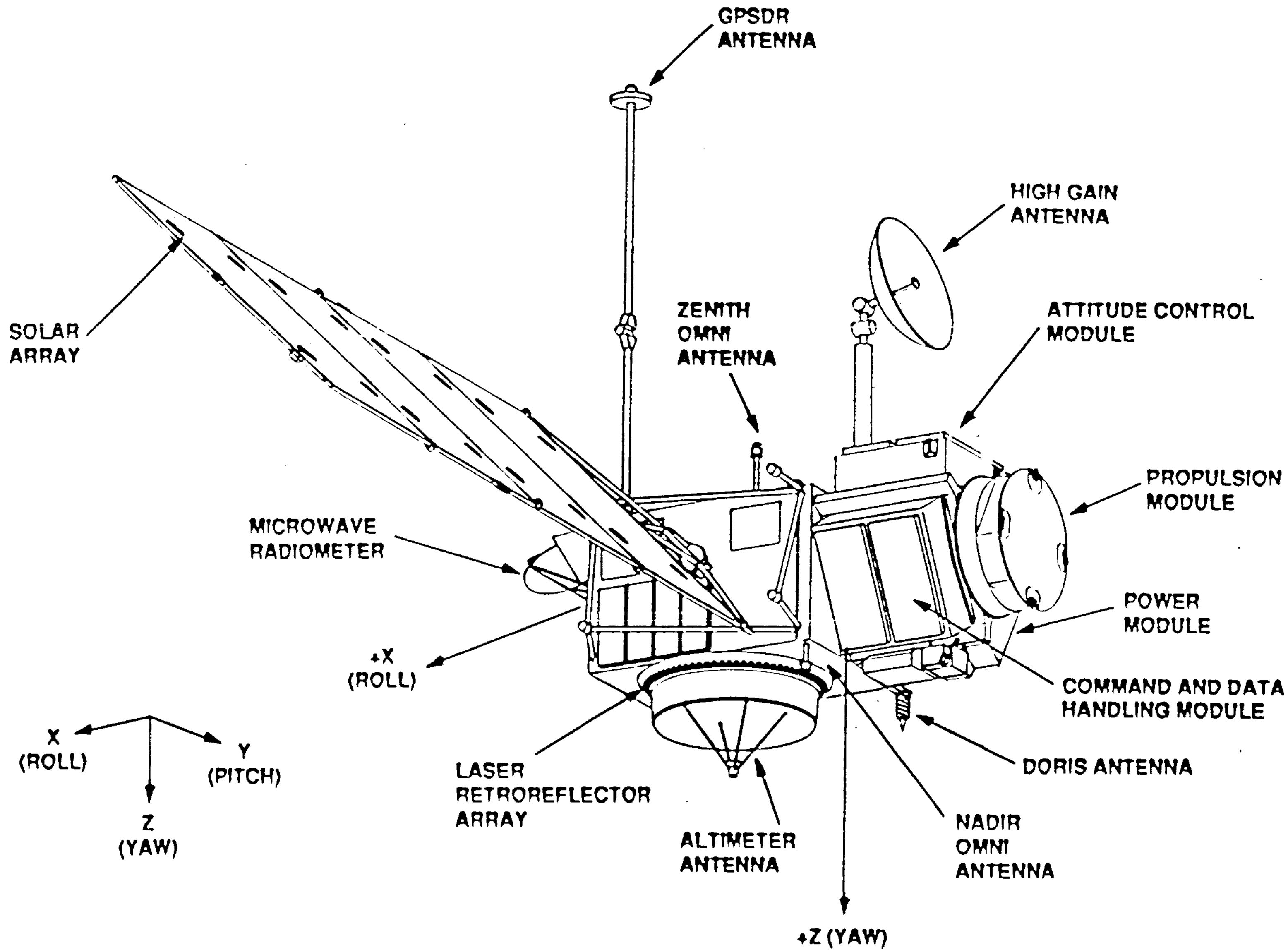
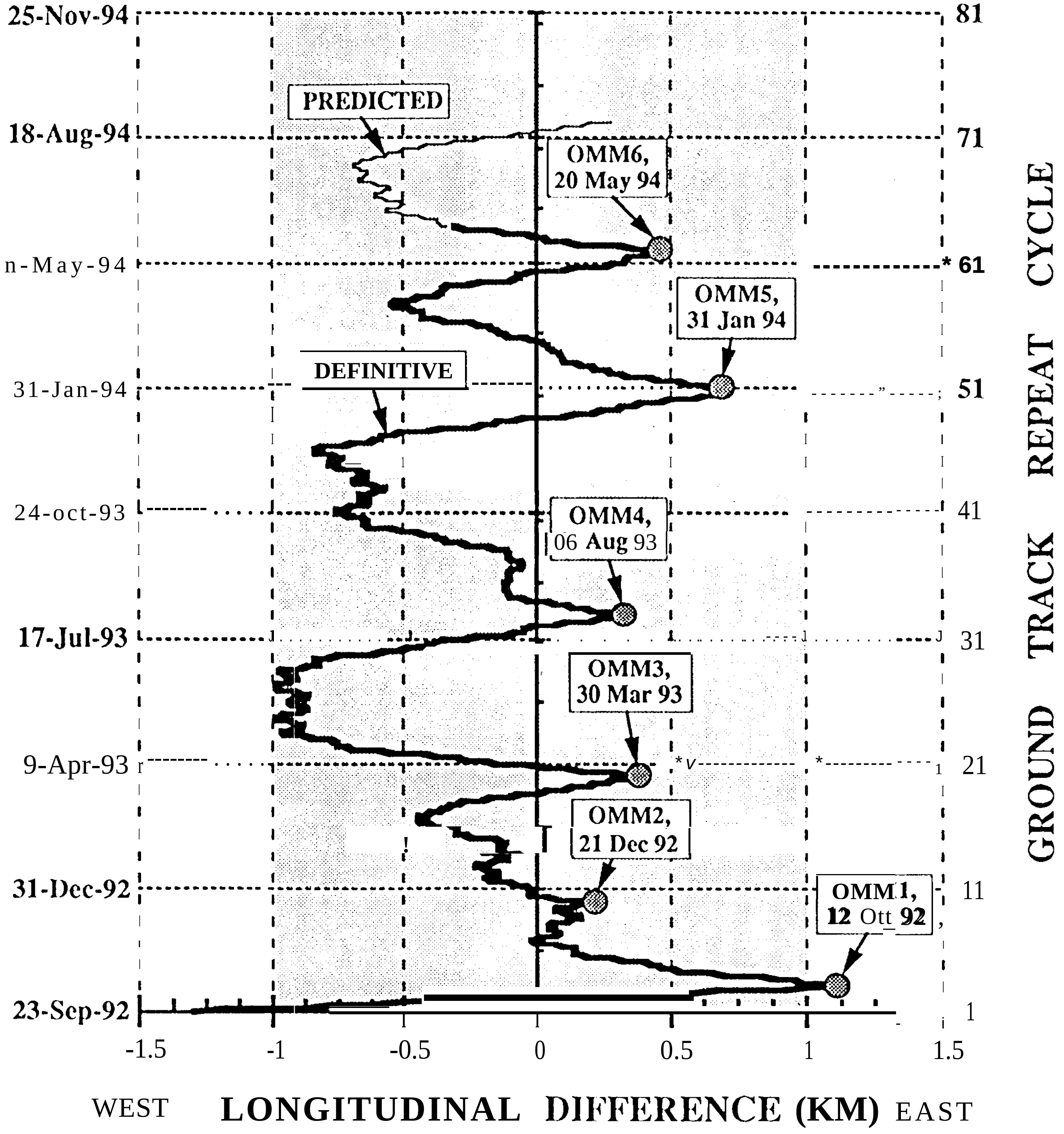

GPSDR
ANTENNA
HIGH GAIN
ANTENNA
SOLAR
ARRAY
ZENITH
OMNI
ANTENNA
ATTITUDE CONTROL
MODULE
PROPULSION
MODULE
MICROWAVE
RADIOMETER
POWER
MODULE
+X
(ROLL)
COMMAND AND DATA
HANDLING MODULE
X
(ROLL)
Y
(PITCH)
Z
(YAW)
LASER
RETROREFLECTOR
ARRAY
DORIS ANTENNA
ALTIMETER
ANTENNA
NADIR
OMNI
ANTENNA
+Z (YAW)

Fig. 2-1



PREDICTED
DEFINITIVE
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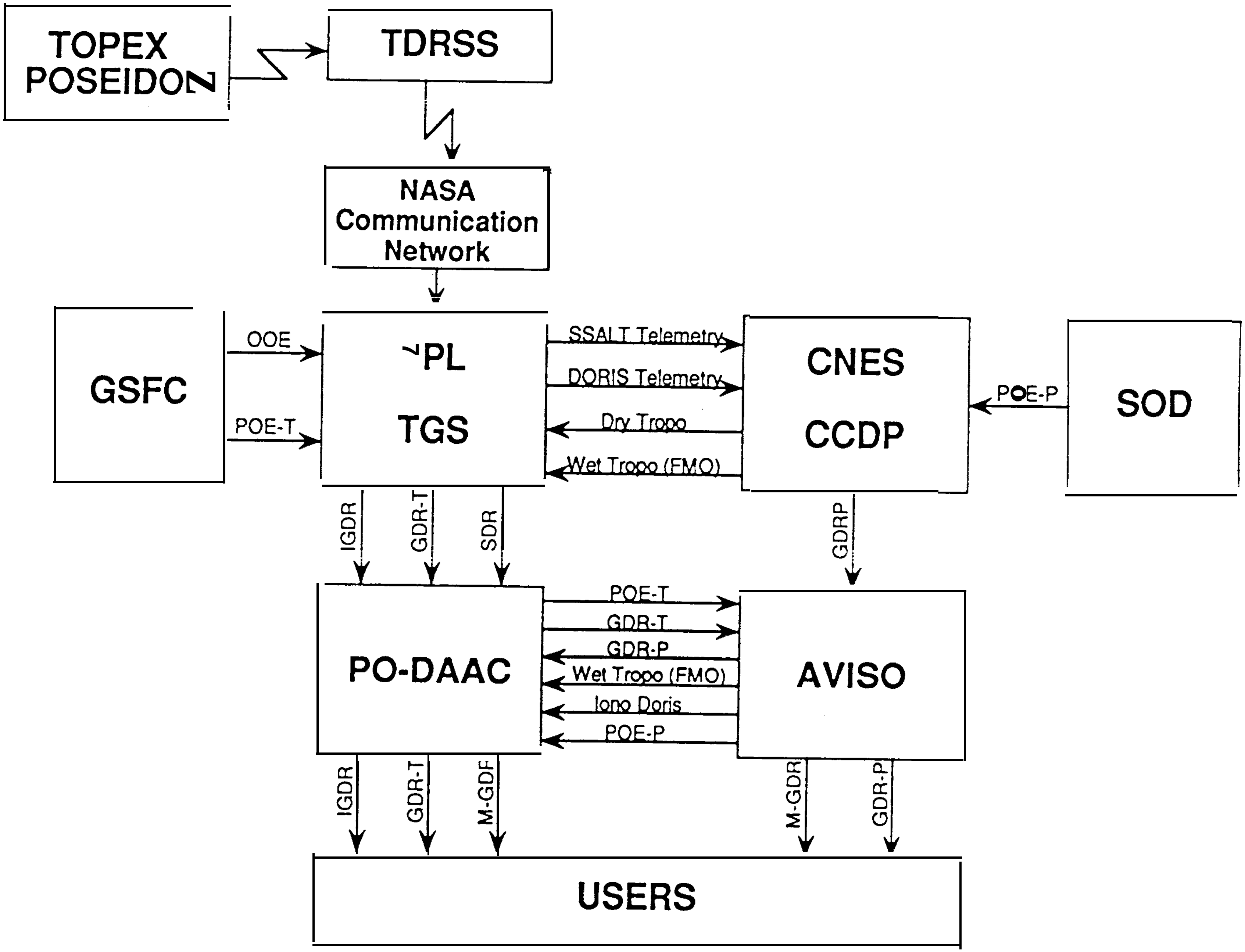
OMM5, 31 Jan 94
OMM4, 06 Aug 93
OMM3, 30 Mar 93
OMM2, 21 Dec 92
OMM1, 12 Ott 92
25-Nov-94
18-Aug-94
n-May-94
31-Jan-94
24-oct-93
17-Jul-93
9-Apr-93
31-Dec-92
23-Sep-92
81
71
61
51
41
31
21
11
1
-1.5
-1
-0.5
0
0.5
1
1.5
GROUND TRACK REPEAT CYCLE
WEST
LONGITUDINAL DIFFERENCE (KM)
EAST

Fig 2


TOPEX
POSEIDON
TDRSS
NASA
Communication
Network
GSFC
OOE
POE-T
PL
TGS
SSALT Telemetry
DORIS Telemetry
Dry Tropo
Wet Tropo (FMO)
CNES
CCDP
POE-P
SOD
IGDR
GDR-T
SDR
GDRP
PO-DAAC
POE-T
GDR-T
GDR-P
Wet Tropo (FMO)
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AVISO
IGDR
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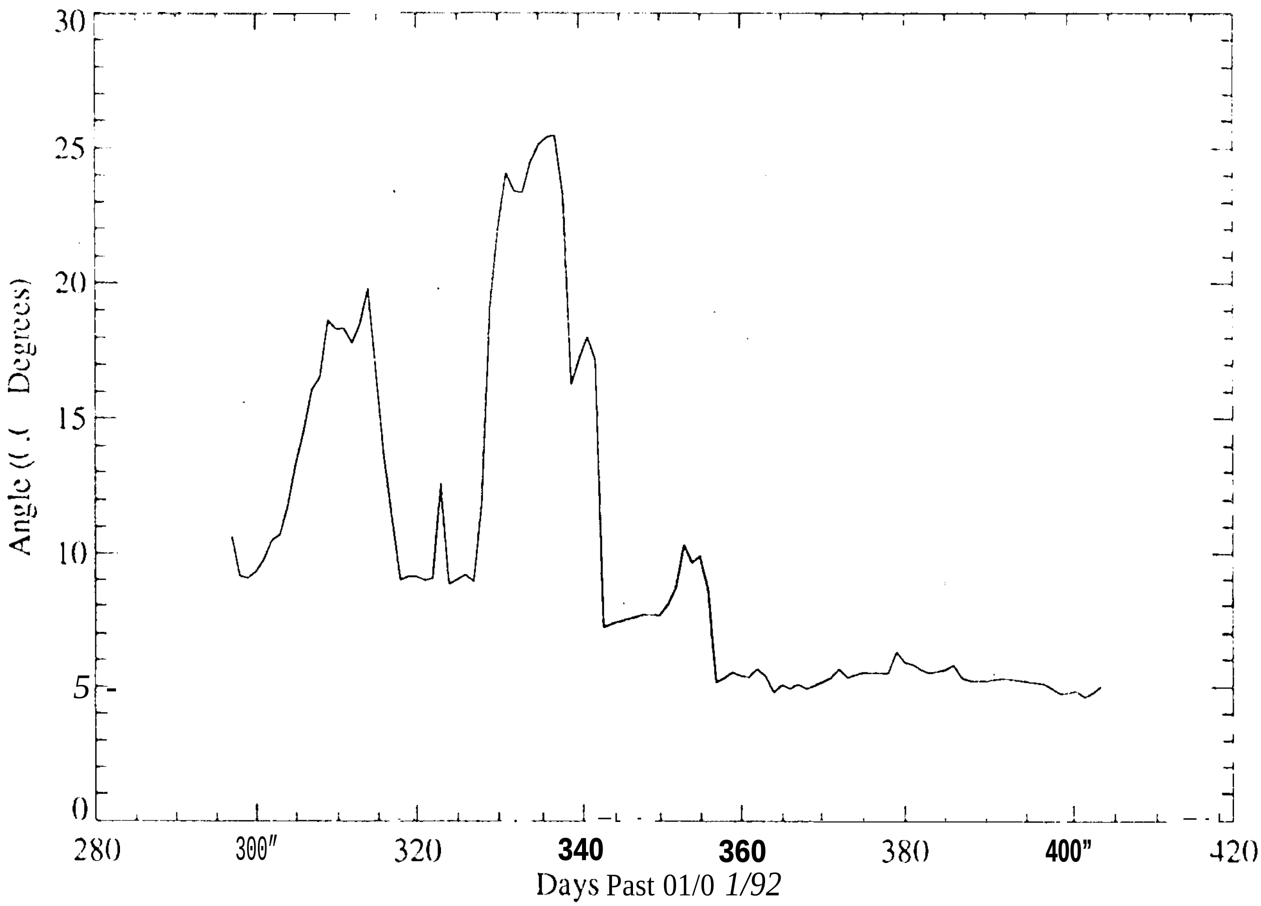
GDR-P
USERS

Fig. 3



30
25
20
15
10
5
0
Angle ((.(Degrees)
280
300"
320
340
360
380
400"
420
Days Past 01/0 1/92

Fig 4

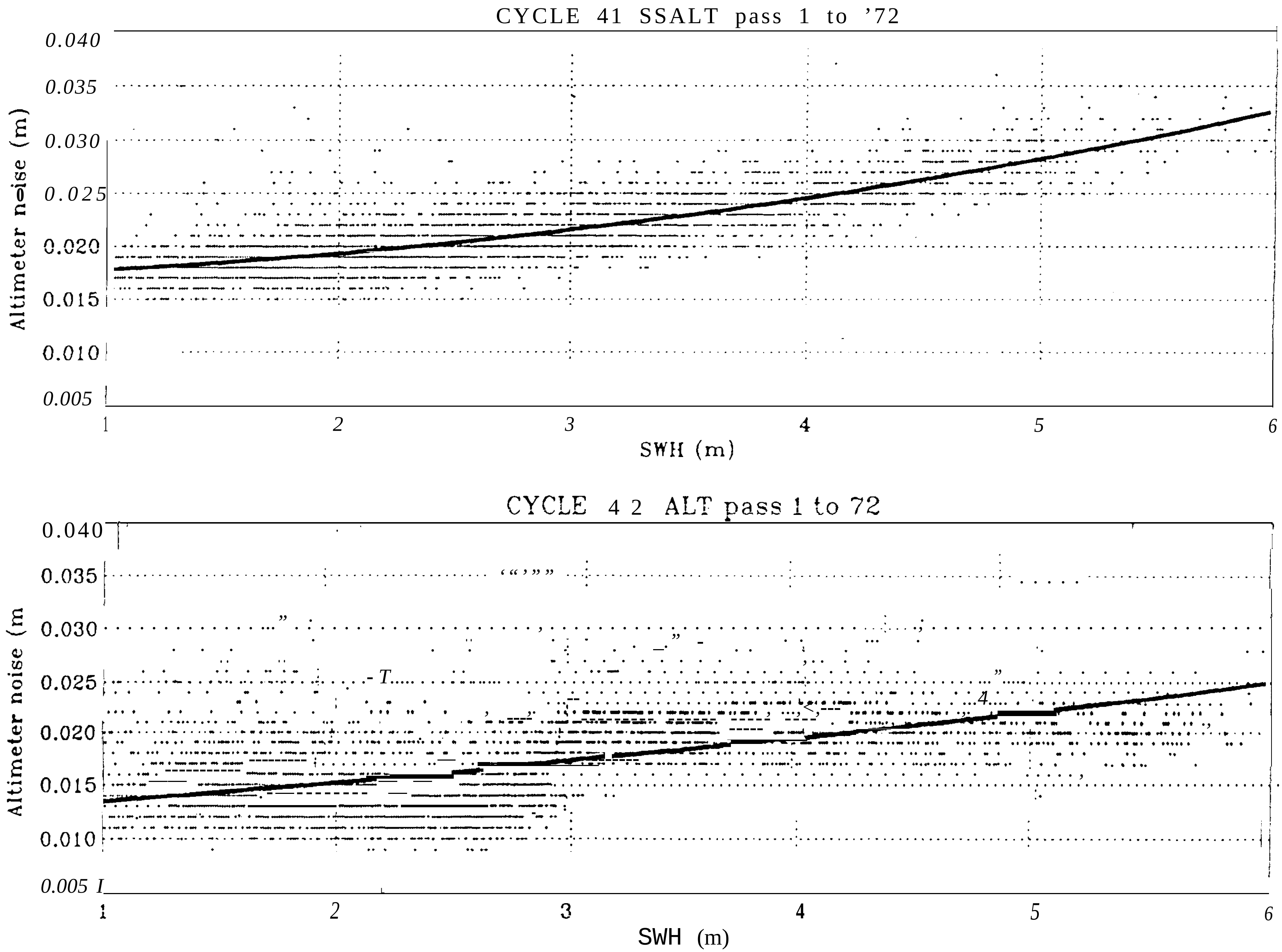

CYCLE 41 SSALT pass 1 to '72
Altimeter noise (m)
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
1
2
3
4
5
6
SWH (m)
CYCLE 42 ALT pass 1 to 72
Altimeter noise (m
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
1
2
3
4
5
6
SWH (m)

Fig 5